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Influence of thermal ageing on the mechanical properties of an additively manufactured photopolymer used in soft tooling applications

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Abstract
In recent years, direct rapid soft tooling based on inserts manufactured additively by light reactive photopolymer curing has become a solid alternative to classic tooling based on subtractive machining of metals for prototyping and pilot production of polymer parts by injection moulding. Reported numbers of injection-moulded parts per insert are in the low to medium three-digit range. This, however, is based on using additive manufacturing for the production of both mould halves. It was found that combining a soft tooling insert on one mould half and a metal insert on the other half can increase insert lifetime to more than 10 000 parts in acrylonitrile butadiene styrene (ABS) with a negligible influence of insert wear on the dimensional stability of the injection-moulded parts. Photopolymers are known for their very low heat conductivity compared to metals and their sensitivity to elevated temperatures leading to degradation and negative effects on their mechanical properties. Considering heat transfer laws, it can be assumed that most thermal energy brought into the cavity during the plastic injection is conducted away through the steel half of the mould, thus leading to a significant reduction of the thermal ageing of the photopolymer insert. This research supports the quantification of the influence of thermal ageing on insert lifetime by performing experiments with photopolymer samples aged thermally after exposure to different elevated temperature levels for different time spans.

Additive Manufacturing, Injection Moulding, Soft Tooling

1. Introduction

Direct rapid soft tooling based on vat photopolymerization can be used for the production of small to medium numbers of polymer parts by injection molding [1, 2, 3]. [4] found an outstanding lifetime of more than 10 000 shots for a ceramic-composite insert (material name: Somos Perform) used in a hybrid tooling setup. It was therefore decided to test this material by performing dynamic mechanical analysis (DMA) with a virgin specimen as well as tensile tests with thermally treated specimens to gain data for a better understanding of this unexpected material behavior.

2. Materials and Methods

During the DMA, a specimen was heated three times up to 240°C. During the tensile tests, 70 specimens following ISO 527-3 [5] were used. 10 specimens without additional thermal treatment were examined during a reference test. The remaining 60 specimens were exposed to thermal treatments at twelve different conditions with a duration of 10, 20, and 30 minutes at temperature levels of 100, 150, 200, and 240°C with 5 specimens at each level. No data are available for 10 minutes at 240°C due to misalignment of specimens.

3. Results

Figure 1 shows storage modulus (stored energy) as well as loss modulus (dissipated energy). The peak of the loss modulus curve indicates the glass transition temperature Tg. For the first heating run, Tg is at about 360 K (87°C) which is close to the 81°C reported in the material data sheet [6]. For the two following runs, Tg is ca. 20 K higher. Since the thermal post curing of the specimen was performed at a maximum temperature of 160°C only, the findings indicate that post curing at a higher temperature can increase Tg.

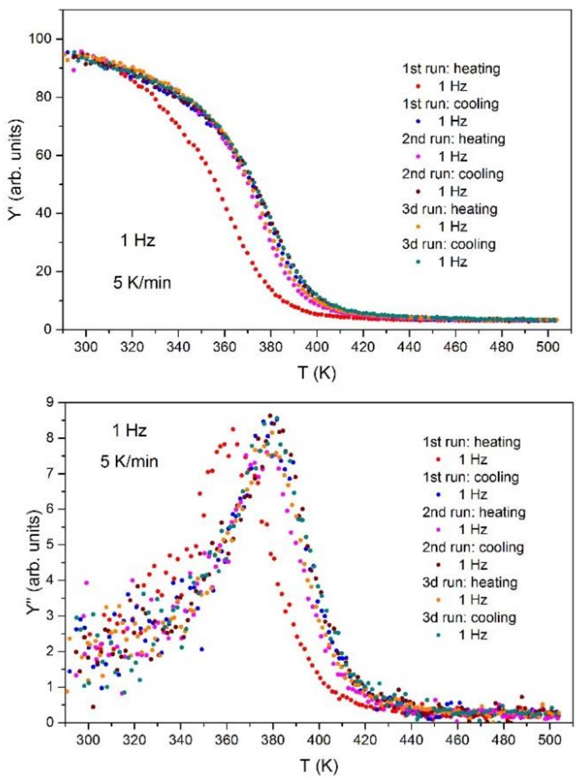

Figure 1. Storage modulus (top) and loss modulus (bottom).

Longer heat treatments at high temperatures resulted in a color change of the material through the whole specimen. No clear influence of the thermal treatments on elongation at break was found in the tensile test results. It remained between 1.7% and 2.2% with a maximum standard deviation of 0.3% for the different thermal treatments (Figure 2) which is significantly higher than the elongation at break provided in [6], i.e. 1.1-1.2%.

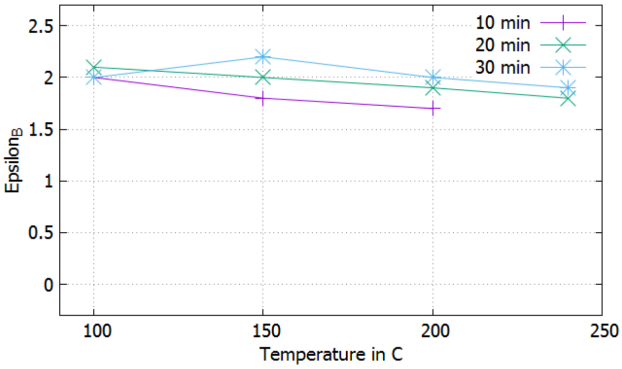

Figure 2. Elongation at break for different thermal treatments.

The forces at an elongation at break of 1.4% are presented in Figure 3 and Table 1. For example, the force for specimens treated at 240°C for 30 minutes (640.72 ± 4.67 N) is 10.3% higher than the force for the reference specimens (580.64 ± 9.57 N). A possible explanation is the post curing: during thermal post curing, the printed parts were heated up by 10°C per hour up to a temperature of 160°C. Figure 3 suggests that heat treatment at the higher temperature levels led to changes in the material since higher forces were required to elongate the specimen (Table 1). This is congruent with the findings during the dynamic mechanical analysis.

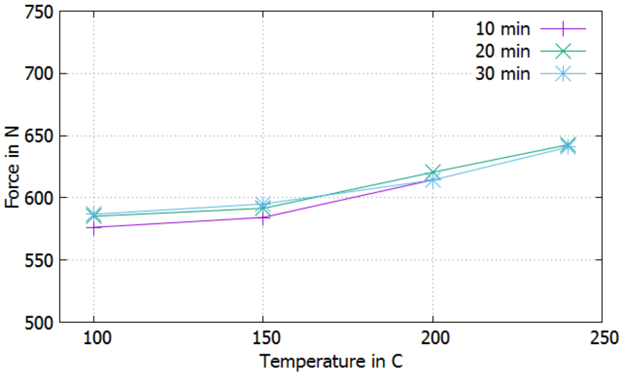

Figure 3. Average forces (in N) at an elongation of 1.4% for different thermal treatments.

Table 1 Average forces and standard deviations (in N) at an elongation of 1.4% for different thermal treatments.

	10 min	20 min	30 min
100°C	576.3 ± 6.8	585.2 ± 8.9	586.8 ± 5.3
150°C	584.3 ± 6.9	591.6 ± 5.6	595.1 ± 9.3
200°C	614.5 ± 4.8	621 ± 12	614.3 ± 7.8
240°C	-	642.7 ± 2.6	640.7 ± 4.7

The stress-strain curves for the samples with 30 minutes at 240°C as well as without heat treatment are presented in Figure 4. It seems that the change between elastic and plastic behaviour happens abruptly at about 0.25 %.

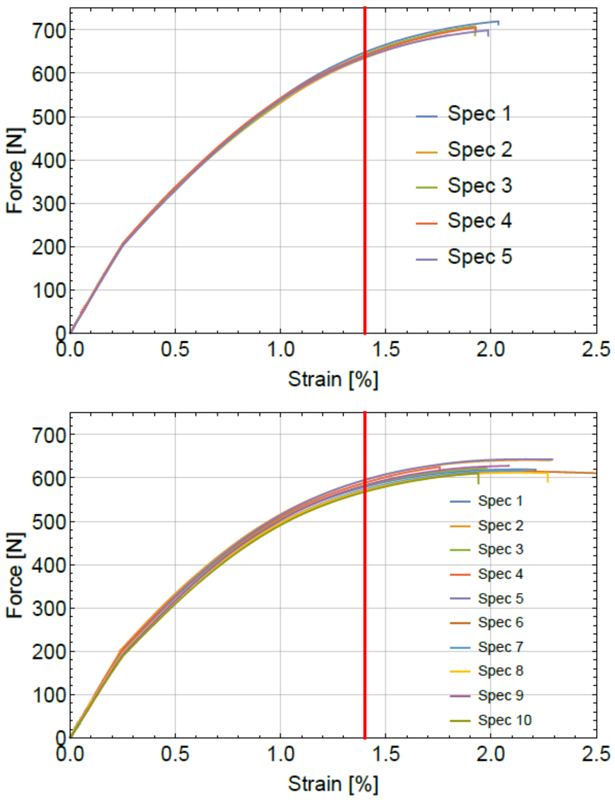

Figure 4. Stress-strain curves for heat treatment (30 min at 240°C, top) and the reference without heat treatment (bottom).

4. Summary, Conclusion and Future Research

Dynamic mechanical analysis (DMA) as well as tensile tests were performed with thermally treated specimens in a photopolymer with a reported insert lifetime [4] of more than 10 000 shots in direct rapid soft tooling.

The results led to the conclusion that heat treatment at the higher temperature levels resulted in changes of material properties as higher forces were required to elongate the specimen. These improved properties support the successful implementation of direct rapid soft tooling in process chains employing additive manufacturing for precision engineering.

Future research on creep and thermal ageing of photopolymer materials is highly likely to facilitate lifetime predictions for injection molding inserts manufactured by light reactive photopolymer curing.

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